1952

Proposal "The influence of residual stress on column strength" and "The mechanical properties of rolled shapes and plates," 1952

L. S. Beedle

1-8-52 Residual Stresses

REPORT NO.

DATE

FRITZ ENGINEERING LABORATORY
LEHIGH UNIVERSITY
REPORT

TO

BY

1.5B

LEHIGH UNIVERSITY
DEPARTMENT OF CIVIL ENGINEERING AND MECHANICS
BETHLEHEM, PA.

ADDRESS REPLY TO:
FRITZ ENGINEERING LABORATORY

PHONE
BETHLEHEM 7-5071
FRITZ E. L. OFFICE EXT. 258
HYDRAULICS LAB. EXT. 279

January 8, 1952

File C-2A/220A

Mr. Shortridge Hardesty
Chairman, Column Research Council
Room 407
101 Park Avenue
New York 17, N. Y.

Re: Residual Stresses in Columns

Dear Mr. Hardesty:

The attached proposal is submitted to the Column Research Council for research on the topic, "The Influence of Residual Stress on Column Strength and The Mechanical Properties of Rolled Shapes and Plates". The work would be a continuation of research conducted in 1950-51 at the Fritz Engineering Laboratory and would follow the work of the Pilot Investigation which has already been submitted to you under date of October 22, 1951.

In view of the forthcoming meeting of a small group to consider the residual stress problem, sufficient copies are included for your distribution to them if you wish. This proposal is of a more general nature than those submitted previously and although he has not seen it, Mr. Jones indicated by phone that such a statement might be useful as an agenda for the "special committee" meeting.

Sincerely yours,

Lynn Beedle

Lynn S. Beedle
Assistant to the Director

LSB:jb

cc: Mr. T. R. Higgins
Dr. B. G. Johnston
Mr. J. Jones

LEHIGH UNIVERSITY
DEPARTMENT OF CIVIL ENGINEERING AND MECHANICS
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LEHIGH UNIVERSITY
FRITZ ENGINEERING LABORATORY
DEPARTMENT OF CIVIL ENGINEERING AND MECHANICS
BETHLEHEM, PENNA.

PROPOSAL

The Influence of Residual Stress on Column Strength

and

The Mechanical Properties of Rolled Shapes and Plates

I. INTRODUCTION

In 1946 Committee D of Column Research Council stated the following in their list of recommendations for further research:

> "Rolled sections, sections built up by welding, and sections fabricated by bolting or riveting generally have material residual stresses, both compression and tension, in the member. In addition, the member may have residual moments and shears incident to relative deformations in the fabrication of the structure of which the member is a part. The effect of these residual stresses on the strength of compression members is subject to question. Some experimental results indicate little or no effect; however, for certain conditions the effects may not be negligible. This investigation is primarily experimental."

Some of the work done since that time has been summarized in a previous report-proposal (1). The results of recent tests conducted at Lehigh University show that the strength of a concentrically loaded structural steel column in the as-rolled condition cannot be predicted on the basis of applying the tangent modulus concept to the results of small coupon tests. The reductions below "coupon test" values are shown for three columns in Fig. 1. (A1)

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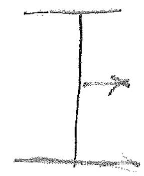
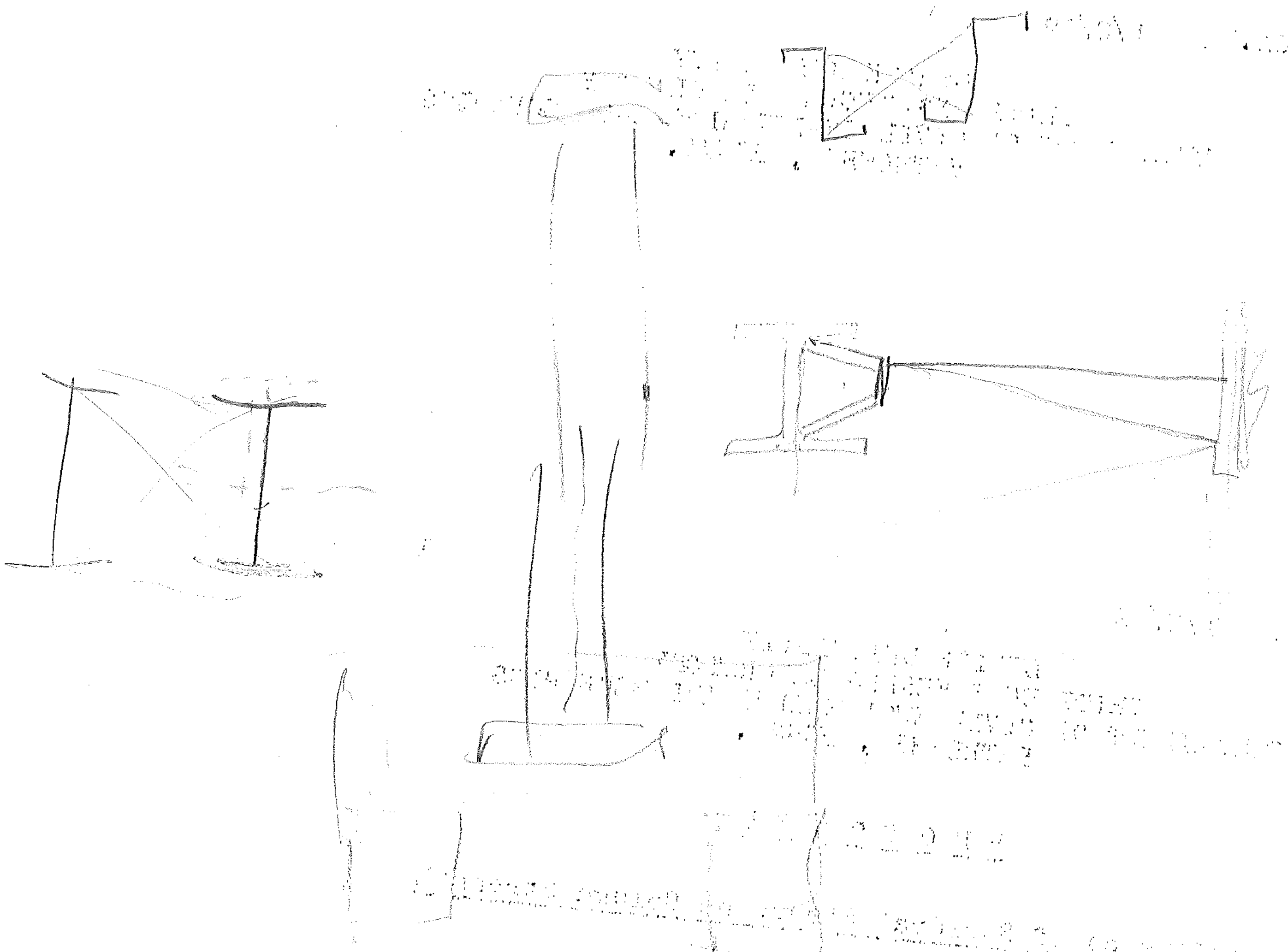
(1) Lynn S. Beedle, "The Influence of Residual Stress on Column Strength - A Proposed Pilot Investigation", Fritz Laboratory Report No. 220A.3, October 22, 1951.





Is Torsion covered sufficiently

GWinter wants to see us prevent all torsion – provide lateral support to comp. flge

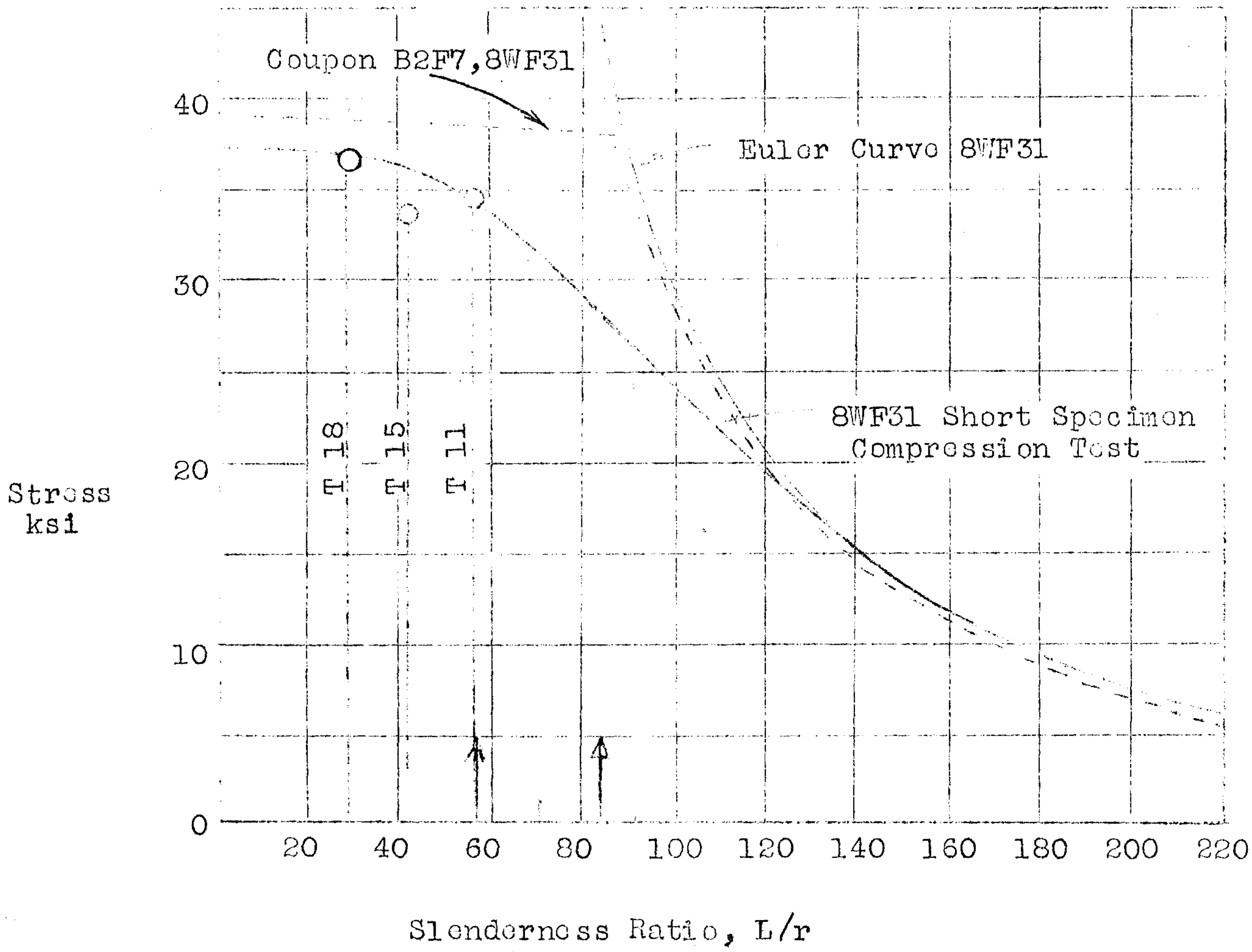


Fig. 1.

The open circles in Fig. 1 are plotted at the maximum loads carried by three concentrically loaded steel columns of 8WF31 cross section. The columns were free to rotate at the ends about the strong axis but were restrained at the ends against bending in the weak direction. The dotted line is the column curve derived from coupon test results using the tangent modulus theory; the heavy solid curve will be described later.

Assuming a parabolic distribution of residual stress with a maximum compression stress of 20 ksi and a maximum tension of 10 ksi, the theoretical column curves of Fig. 2 (2) are obtained.

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(2) Yang, C. H., Beedle, L. S., and Johnston, B. G., "Residual Stress and the Yield Strength of Steel Beams", Fritz Laboratory Report No. 205B.8, Section VII, September 10, 1951.

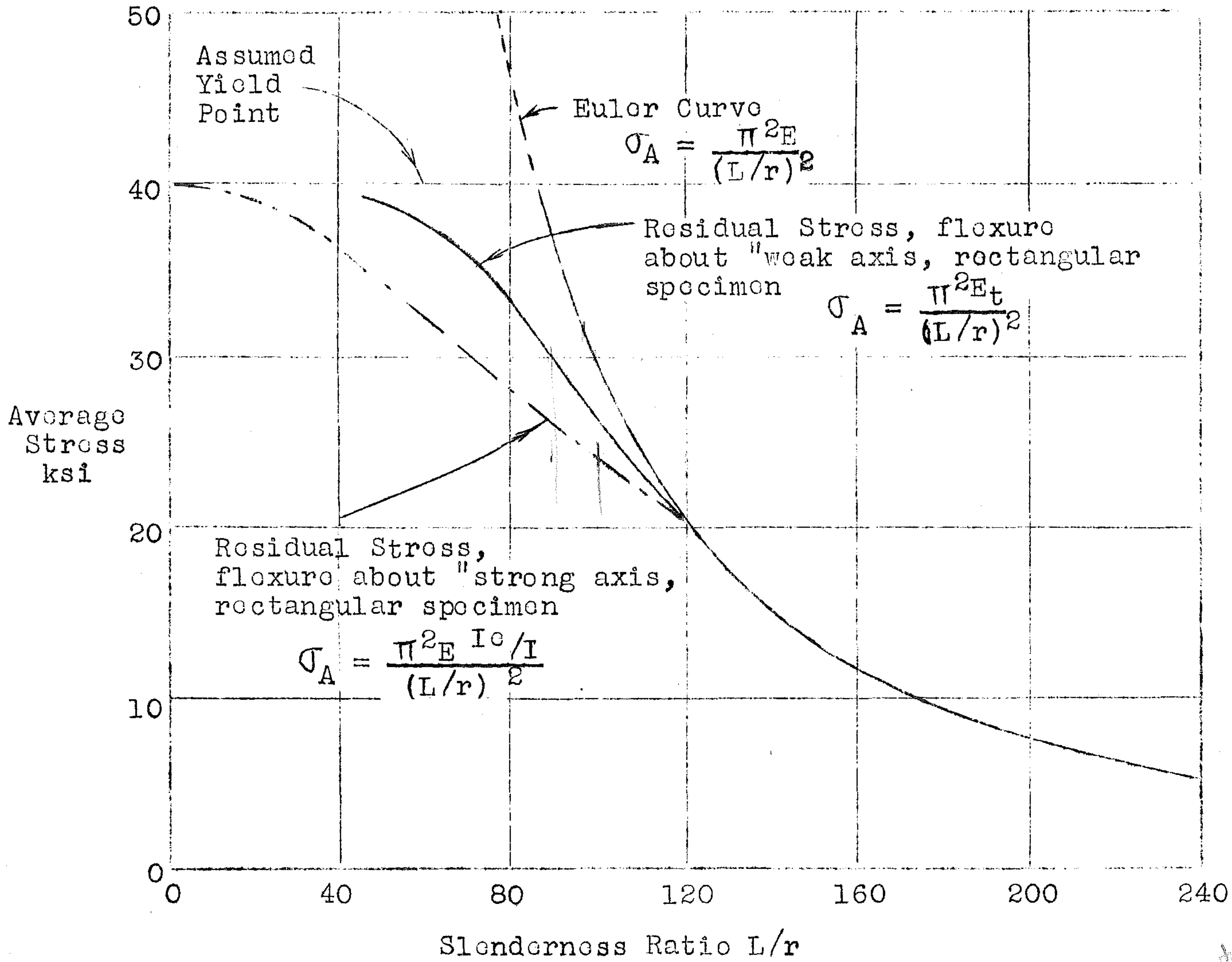


Fig. 2.

In view of the apparent inadequacies of the theory as indicated by experiments, the following questions should be answered:

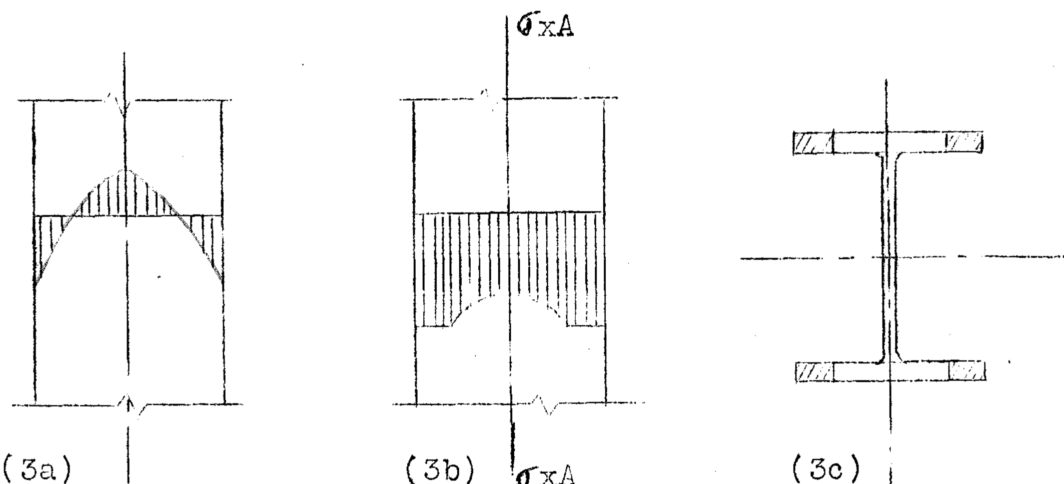
A. DO PRESENT FORMULAS OR DESIGN RULES FOR STEEL COLUMNS REQUIRE MODIFICATION?

The Column Research Council has gone on record to adopt the tangent modulus formula. If based on individual coupon test results, this formula will not correctly predict the strength of as-delivered steel columns (1); it is thus necessary for design purposes to explore further a means of accounting for residual stress in the tangent modulus concept ... or else to modify the statement.

The reductions in column strength described earlier have been attributed in the past to other causes (eccentricity, curvature, etc.) which do offer a plausible explanation and which do have a definite effect on the column strength curve. However, it now seems probable that residual stress is the predominant factor in reducing the strength of structural steel columns below the yield stress level. Osgood [3] has made a general statement of the basic problem and Lehigh work summarized in a forthcoming Welding Research Supplement paper has treated specific cases.

B. BY HOW MUCH HAS THE STRENGTH OF COLUMNS BEEN OVER-ESTIMATED ASSUMING 33000 PSI YIELD POINT BASED ON MILL TESTS?

This is a function of slenderness ratio, since not all columns are affected by residual stress. In some ranges, the over-estimation has been very little or none at all. For others, the evidence indicates a considerable error. There are two factors which cause these reductions in load-carrying capacity. One factor is local instability. Suppose, for example, that the distribution of residual stress in a column flange is that shown in Fig. 3a. After a stress is



(3a) (3b) (3c)

added to the flange to give a distribution such as that shown in Fig. 3b, the flange edges will have yielded and the flange buckling strength will have been reduced. Following the buckling of certain shapes, these elements will no longer carry the stress equal to the yield point value; even if general buckling of the column did not occur, the column would not be able to carry a load corresponding to the yield-point stress.

---

(3) Osgood, W. R., "Residual Stresses in Columns", presented at the June, 1951 meeting of the First U. S. National Congress of Applied Mechanics.

The second factor causing a reduction in strength below the values predicted by coupon tests is instability due to loss of elastic cross-section. Referring to Fig. 3c, the maximum strength of a structural steel column is a function of the part remaining elastic (2). For certain L/r values, the average stress is low enough so that bending commences while the member is still elastic. Residual stress would consequently have no effect. (L/r greater than 120 in Fig. 2). However, at higher stresses yielding of part of the cross-section would precede bending of the column and this results in a reduction of the maximum strength.

Referring to Fig. 4 the compressive stress-strain diagram of the material without residual stress would be as shown by the solid line. For a typical pattern of residual stress the dashed line gives the stress-strain curve. If local instability also occurs, typical behavior would be as shown by the dot-dash curve. This is for c-s tests

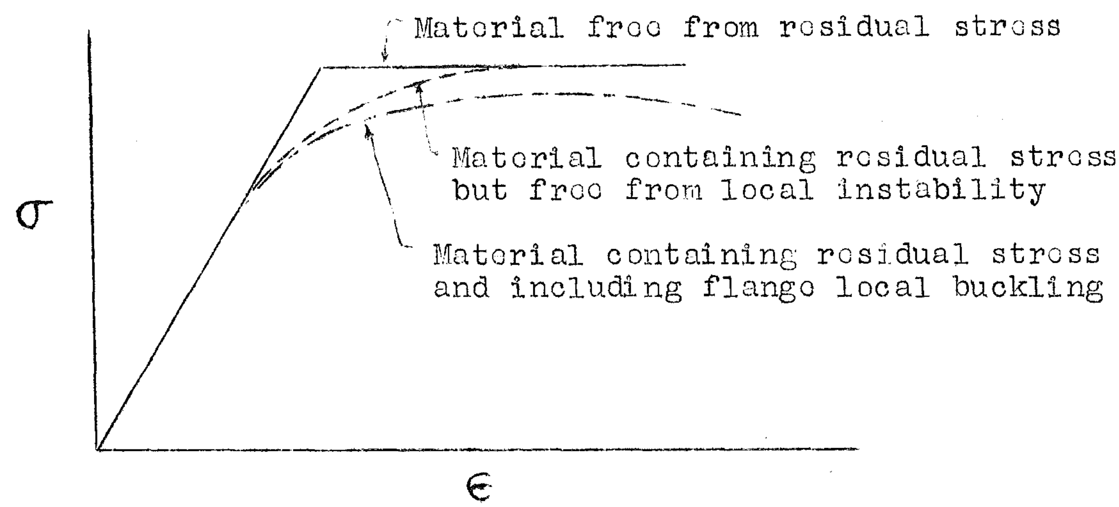


Fig. 4.

C. WHAT SPECIFIC CHANGES SHOULD BE MADE IN COLUMN DESIGN PROCEDURES TO TAKE INTO ACCOUNT RESIDUAL STRESS?

The proposed research should provide the information needed for revising design procedures. Since the observed reductions in column strength have in the past been attributed to other causes, the possibility exists that no change may be required. This will depend on the discrepancy involved in current specifications that do not consider residual stresses as such.

D. <u>WHAT ARE THE MATERIAL PROPERTIES OF PLATES THAT MAKE UP COMPOSITE STRUCTURES?</u>

Committee A has prepared a statement (4) outlining the need for collecting compressive (and corresponding tensile) stress-strain data for plates and shapes.

E. <u>WHAT IS THE BENDING STRENGTH OF VARIOUS ROLLED SHAPES?</u>

Since the material properties of the column test specimens would be determined on the basis of coupon tests, it would be advantageous to explore the relation between coupon test results and experimentally observed bending strength for a large number of rolled shapes. A tentative scheme has been developed for this purpose.

II. P R O P O S A L

In order to provide a basis for answering the above questions, an experimental and analytical project is proposed. The immediate question is the following:

<u>WHAT IS THE BEHAVIOR OF A COLUMN CONTAINING RESIDUAL STRESS AND HOW CAN THIS BEHAVIOR BE PREDICTED WITH SATISFACTORY ENGINEERING ACCURACY?</u>

Three conditions of residual stress are involved:

(a) Residual stress due to cooling:
 (1) Symmetrical distribution
 (2) Unsymmetrical distribution
(b) Residual stress due to cold-straightening or bending.
(c) Fabrication residual stresses due to welding, the punching of holes, and riveting.

Each of these three conditions may have a different influence and each will require study. It will be attempted as early as possible in the program to ascertain the most critical condition for the largest number of columns and concentrate attention on this phase. An outline of the variables in the residual stress problem is included in Appendix I of Ref. 1, page 20. Yield lines in col.

The proposal, then, is to carry out an analytical and experimental program (the experimental portion to be developed in further detail with an advisory committee). The first analytical studies would be an extension of the work of Ref. 2 and of the Pilot Program (1).

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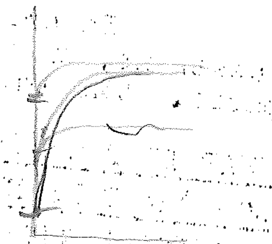
(4) Research Committee A, "Recommendation for Research" (for the purpose of determining the Tangent Modulus), January 5, 1951.

1. Size & Shape

2.

3. Nail Tests

4. { C -
Residual



III. P R O C E D U R E

A number of approaches to correlate column strength with residual stress are possible:

(a) A program of column tests.
(b) From a measured residual stress pattern develop an analytical expression for buckling strength.
(c) Apply the Tangent Modulus concept to the test of a specimen containing residual stress.

Columns would be tested in a range of sizes and shapes (a minimum of four in the WF series) and in a range of equivalent pinned-end slenderness ratios between 50 and 100 90. The reductions below the values predicted by the tangent modulus theory applied to coupons are most severe in this region.

WRO says 90 is too low.

Prior to the testing of columns it would be advantageous to develop analytically the relationship between load and lateral deflection to indicate whether or not the tangent modulus remains a reasonable criterion of strength for columns containing residual stress. In a range of load in which column deflection is important, is a reduction in tangent modulus load also accompanied by a reduction in column strength when compared with members free of residual stress?

WRO wonders what would be done here.

Residual stress measurements should be made for each column tested. For symmetrical patterns, work has already been done in developing analytical expressions for column strength from measured residual stresses (2). Correlation remains to be established with column tests.

Because the yielding process of steel and local flange buckling are phenomena not included in present theories, and both of these conditions are present in as-delivered columns, a series of "cross-section tests" is recommended. The specimens will be selected in such length as to retain residual stresses and to eliminate end effects as much as possible. The pilot program (1) has been set up on this basis, only one shape of cross-section being involved. It follows tests completed at Lehigh in 1950-1951. If the correlation is confirmed by the additional tests outlined, then the next step appears to be a similar program for a limited number of critical shapes, followed by a broader study of a large number of cross-section tests.

The pilot investigation also calls for a determination of residual stress level and the determination of stress-strain diagrams from individual coupon tests. It is necessary to know the material properties of the section as determined by presently-accepted coupon technique, and it is just as important to know the residual stress level in the columns tested. Thus, insofar as the first test program is concerned, columns, coupons, "cross-section tests" and residual stress measurements would all be made from adjacent pieces of one length of steel.

Beyond this point the procedure cannot be specifically outlined. The later emphasis of the program will depend on the correlations observed between column tests, theories based on residual stress measurements, and theories applied to cross-section tests. Because of the influence of local buckling in reducing the ultimate strength of short compression members, a large series of these, carefully selected from material available for later column and coupon tests should be tested early in the program to determine whether or not the average stress at collapse is less than 33 ksi.

It may be unnecessary to measure the residual stress in later tests, since it may be possible to determine the distribution of residuals from the cross-section test by assuming a shape and solving for the necessary constants. Another approximate measure of the residual stress level may also be obtained by observing the load at which the first yield line is formed.

Attention will first be given to WF shapes, followed by angles, channels, and possibly I-shapes.

Consideration will be given to column behavior in different axial planes of bending. If material is to be utilized to the best advantage, different column curves may be useful for different planes of bending.

The work on plates would consist of a collection of such data as requested by Committee A (4).

With regard to the determination of the bending properties of structural steel, a scheme for testing short lengths under bending moment would be developed further. A few pilot tests would then be appropriate.

Specific procedures have been outlined in the Proposed Pilot Investigation (1). Appendix A contains a further description of procedures for cross-section study.

IV. L I M I T A T I O N S

The following limitations are suggested for this particular proposal since it is anticipated that other institutions will also wish to engage in this research:

(1) Primary attention will be given to steel for bridges and building (ASTM A-7) for the column tests.
(2) The main emphasis will be on columns (WF and Angles).
(3) Secondary attention will be given to:
   a. Silicon steel (ASTM A-94)
   b. Low alloys (ASTM A-242)
   c. Shapes of low alloy
   d. Channel and I-section (ASTM A-7)
   e. Bending tests.

Other
① Light Alloy Properties
② Cols of [& I
③ Add'l WF

(4) Only concentrically loaded columns are considered. The problem of the influence of residual stress on columns in frames and columns under combined axial load and bending is an important one but it is not included under the proposed budget. This work is under way separately at Lehigh (5).

V. S U M M A R Y

The reduction in column strength due to residual stress, already demonstrated by test, means that less emphasis need be placed on the curved portion of the stress-strain diagram for small coupons. Attention must be given to the larger variations in average behavior of the material.

This proposal is written for the purpose of continuing studies aimed at developing a method for predicting the behavior of columns containing residual stress (symmetrical and non-symmetrical and due to both cooling and cold-straightening). The program includes:

(a) Pinned-end column tests in a range of sizes, shapes, and slenderness ratios,
(b) Coupon tests and residual stress measurements,
(c) "Cross-section" tests,
(d) Analytical studies to correlate residual stress magnitude with observed column strengths and to evaluate the significance of the tangent modulus load in columns containing residual stress.

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(5) Column Research Council Project O.2.D (Lehigh University), "Columns in Frames". See CRC Quarterly PROGRESS REPORTS.

Ultimately it is hoped that a recommendation can be made as to specific changes in design procedures to take into account residual stress, recognizing that these are already considered in a different guise.

Since the problem is so closely related, the basic material properties are also to be determined in this program for certain shapes and plates of structural grade steel.

VI. B U D G E T A N D P E R S O N N E L

The project would be carried out under the direction of Lynn S. Beedle, Assistant to the Director of Fritz Engineering Laboratory with Research Assistants conducting the test programs. ~~Dr. C. H. Yang and Dr. Bruce G. Johnston have assisted in the preparation of this proposal and the latter would be acting in the capacity of "consultant" in the event the project is approved.~~

Dr. C. [illegible] to act [illegible] is available in the capacity of "consultant" in the event the project is approved.

A three-year program is recommended at $15,000 per year.

APPENDIX A

Cross Section Study Procedures

The procedure for cross-section tests is as follows:

1-23-52 [changes]

(1) Select a member in the as-delivered condition.

(2) Cut a full cross-section length such that only a small percentage of the residual stress is relieved by the cutting. (Criteria have been studied and checked experimentally at Lehigh).

Suggested arbor mill the ends and use hardened plates at ends. Then align with levelling plates.

(3) Test in the flat-end condition, measuring the average shortening for each load increment.

(4) Plot the resulting average stress-average strain curve and determine the tangent modulus at various stress values.

BJ 1-11-52

(5) Plot the column curve for bending in the strong plane with the data of (4) above by solving the equation, $L/r = \pi\sqrt{E_t/\sigma}$.

~~(6) Conduct column tests using same shape at several L/r.~~

Prepared by,

Lynn Beedle

Lynn S. Beedle
Assistant to the Director

Approved: W. J. Eney

W. J. Eney
Head, Department of Civil Engineering and Mechanics

BJ 1-11-52

(6) Conduct column tests with bending permitted only in the strong direction to check the predictions of the plotted column curve developed under Item 5. Use same shape at several L/r.

(7) Assuming that the residual stress pattern has a parabolic distribution across the flange, predict the magnitude of the residual stress at the corners and centers of each flange by a graphical process working from the short column average stress-strain curve. Using these predicted values calculate the reduced moment of inertia in the lateral or weak direction for bending normal to the plane of the web and from these reduced values at various loads calculate a column strength curve for bending in the weak direction.

(8) Conduct column tests with bending permitted in the weak direction and check results with calculated values as obtained by the procedure outlined in Item 7.

Hardened plate
Levelling Plate
Alcoa Hydraulic Head

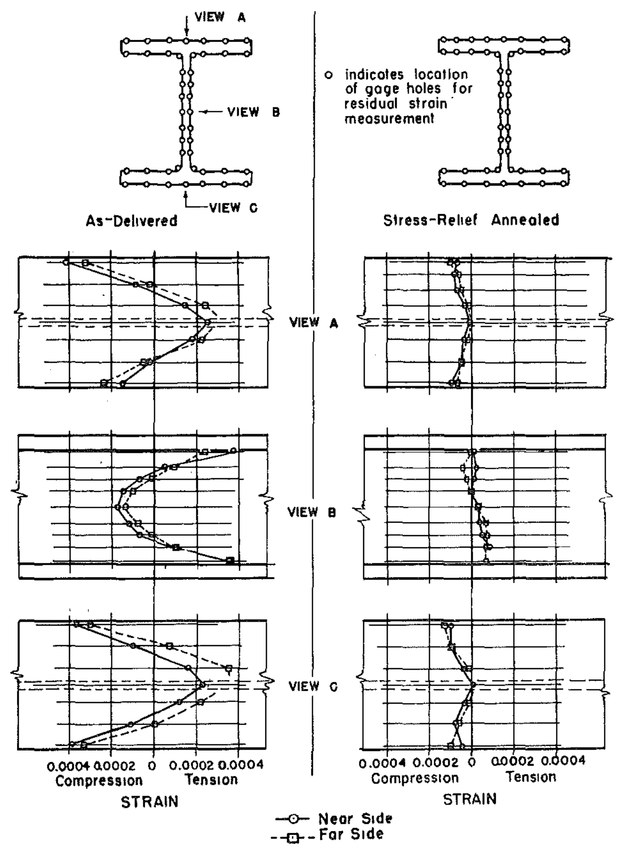


Fig. 26 - RESIDUAL STRAINS IN 8WF67 BEAM FORMED DUE TO COOLING AFTER ROLLING

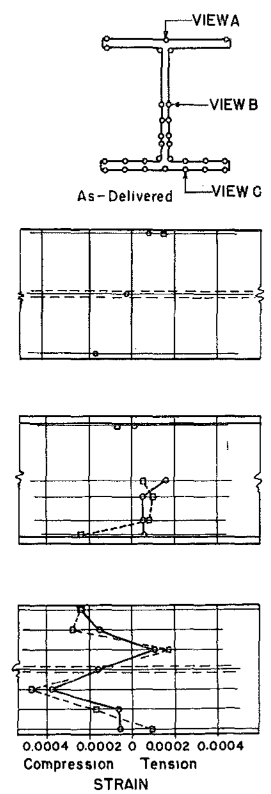


Fig. 27

RESIDUAL STRAINS DUE TO COLD BENDING OF 8WF40 BEAM

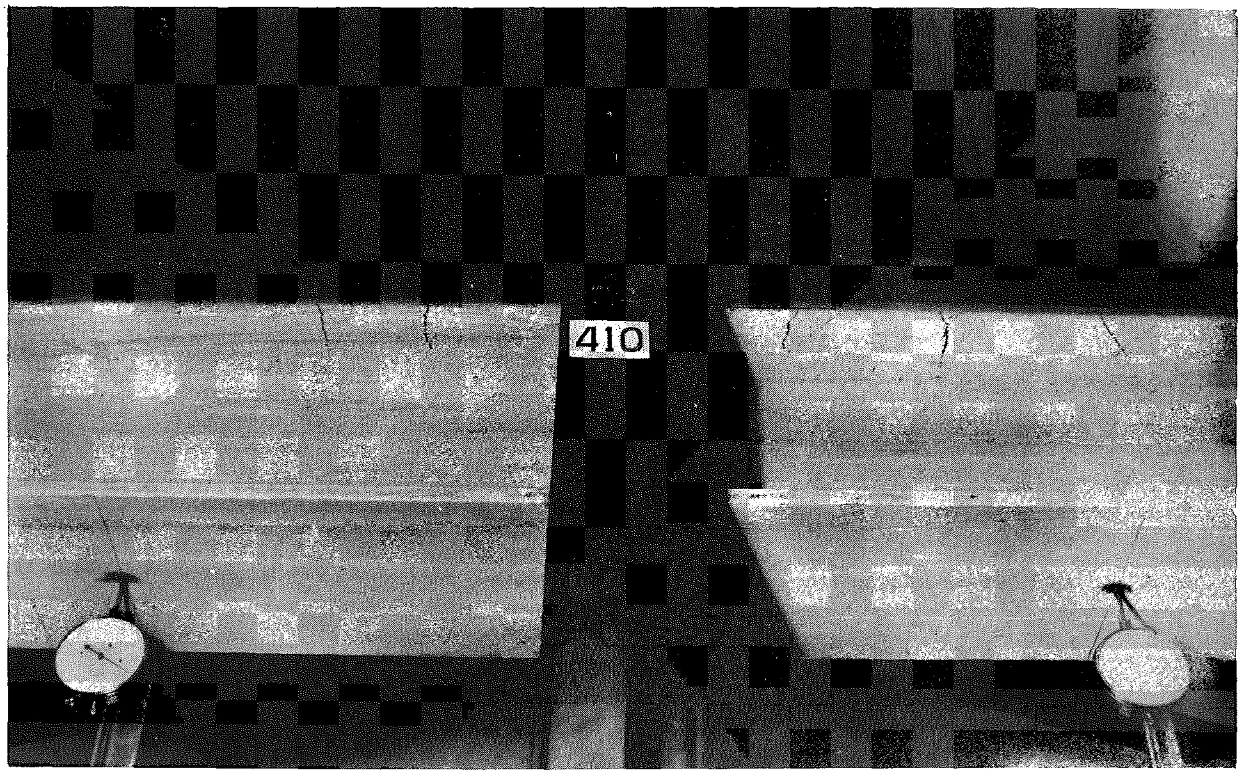


Fig. 28 - Beam 4 showing yield zones at edge of compression flange (upper)

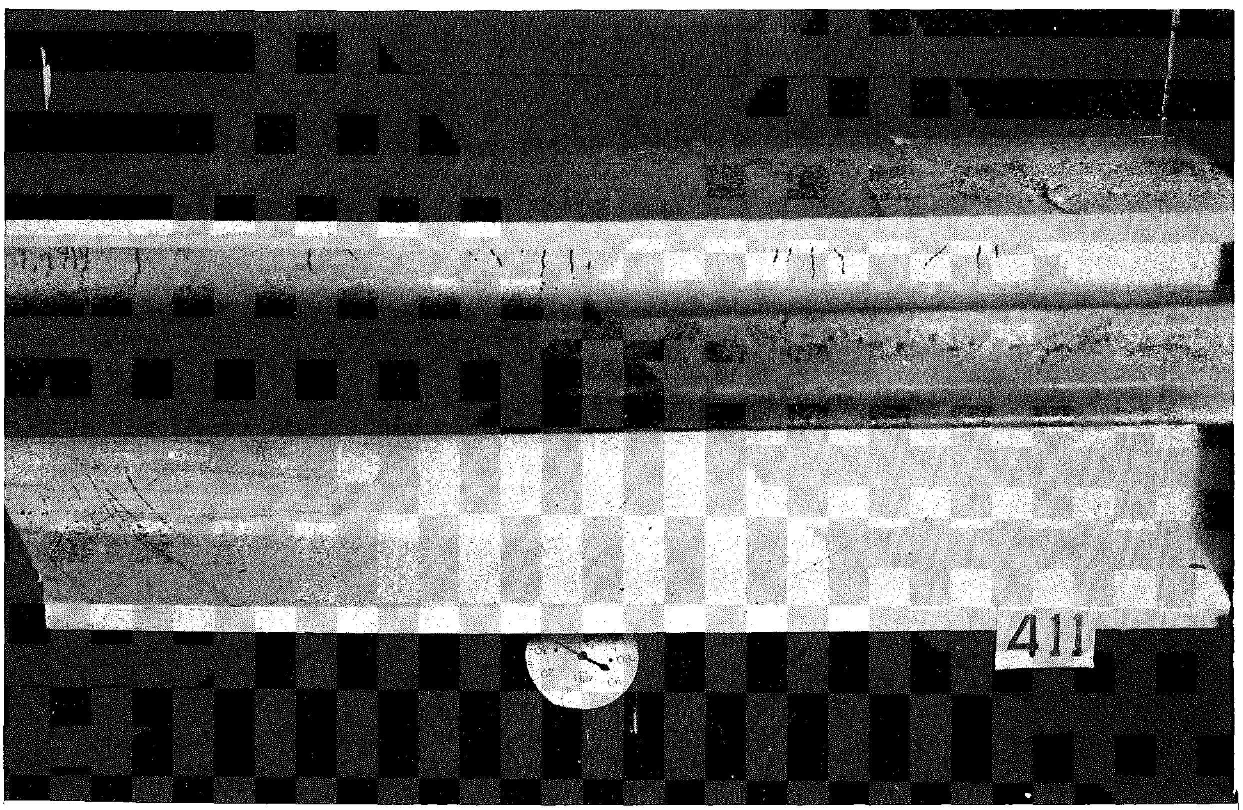


Fig. 29 - Beam 4 showing yield zones in the tension (lower) flange formed subsequent to those in the compression flange

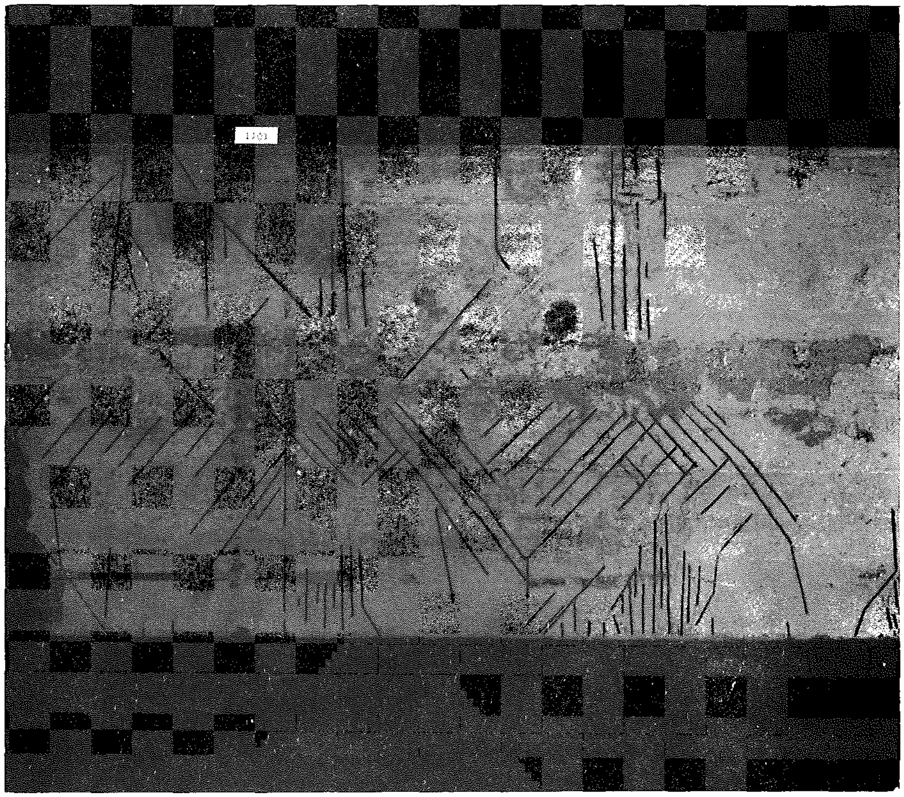


Fig. 30

Example of yield lines formed in flange of 8WF31 section due to cold bending after rolling. (The pattern has been accentuated by tracing the original lines in ink).

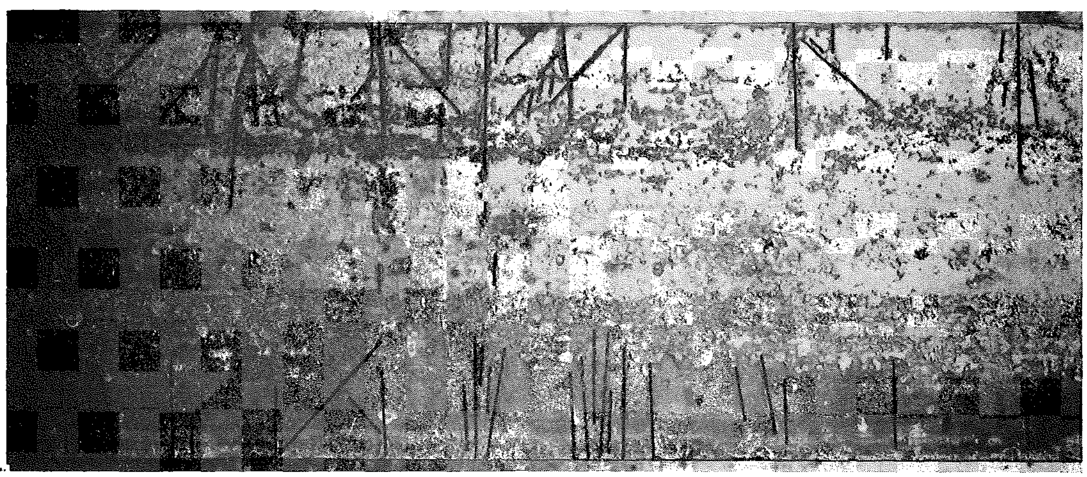


Fig. 31

An additional example of yield lines formed in the flange of a rolled shape due to cold bending. Flexure was probably about the minor axis of the section.

COMPRESSION COUPONS

(Huggenberger Gages)

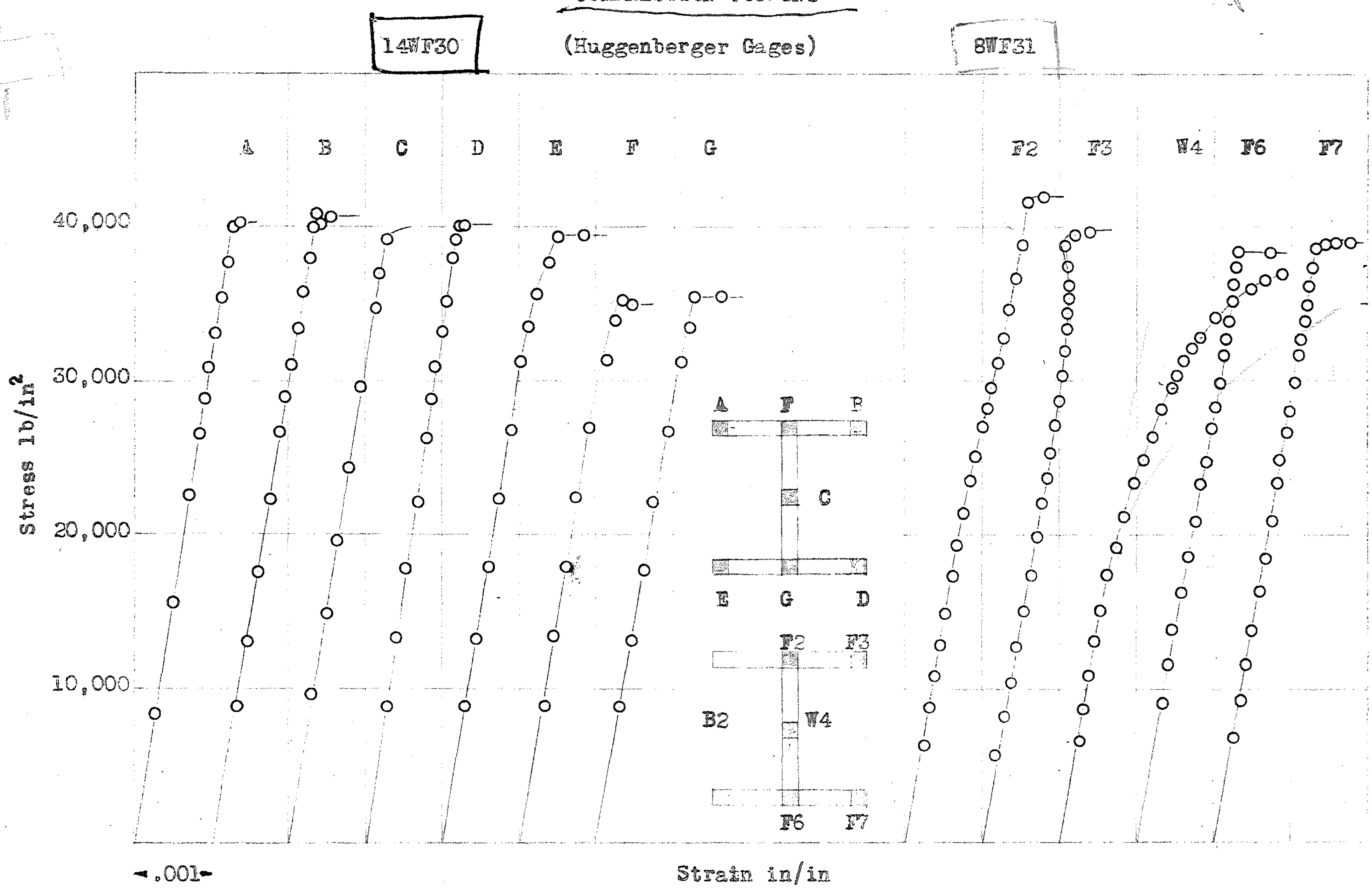


FIG. 4

COMPRESSION
LONGE RANGE OF STRAIN
HUBONKETER

COUPON STRESS-STRAIN CURVES

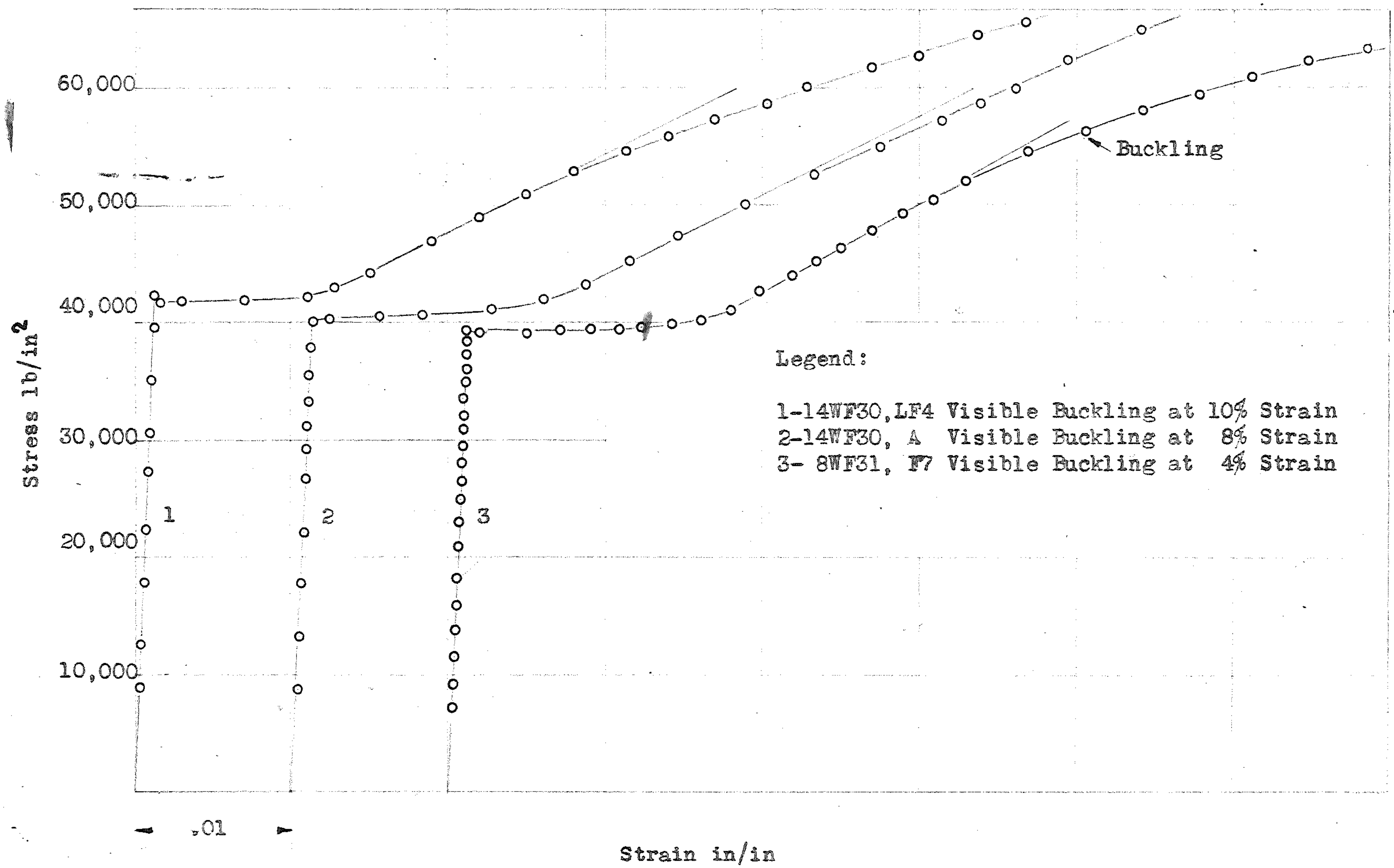
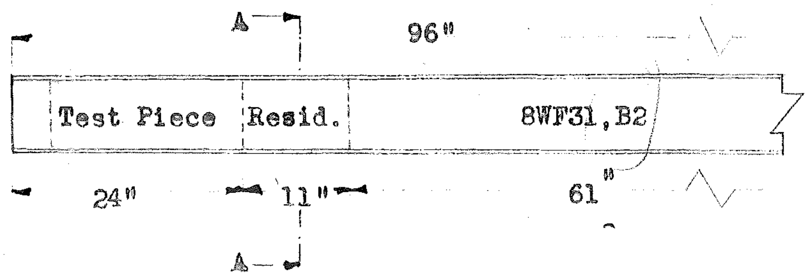


FIG. 5

Successive cuts

6

RESIDUAL STRAIN MEASUREMENTS
8WF31



Position of Holes

Section A-A

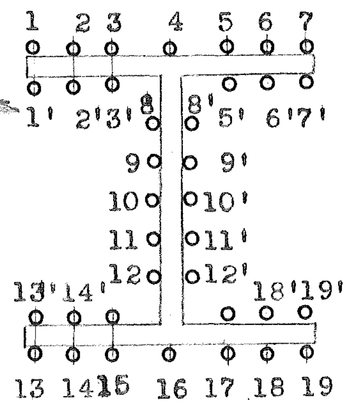


FIG. 10a

Strain in/in
--- Strain after the 11" long section was cut out

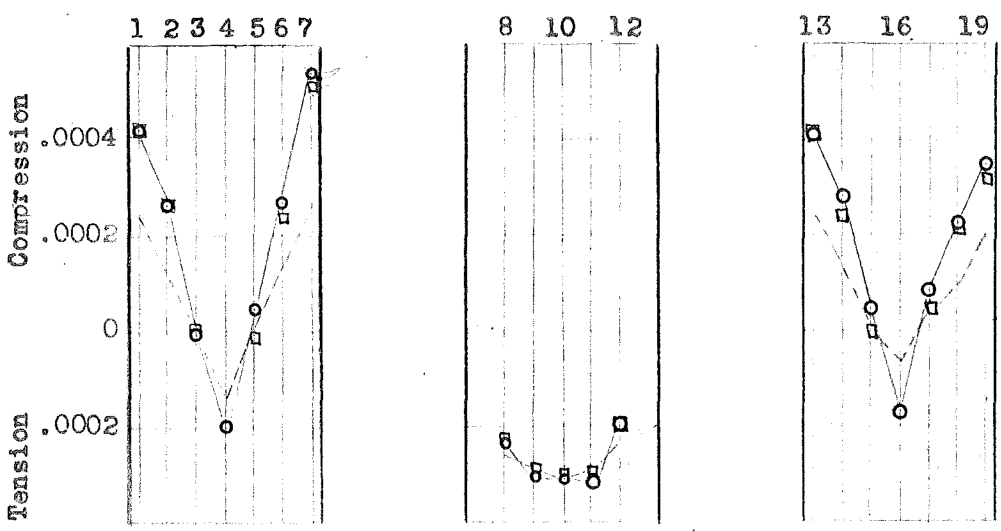


FIG. 10b

□ Points on the opposite side

8WF31 CROSS-SECTION STRESS -STRAIN DIAGRAM

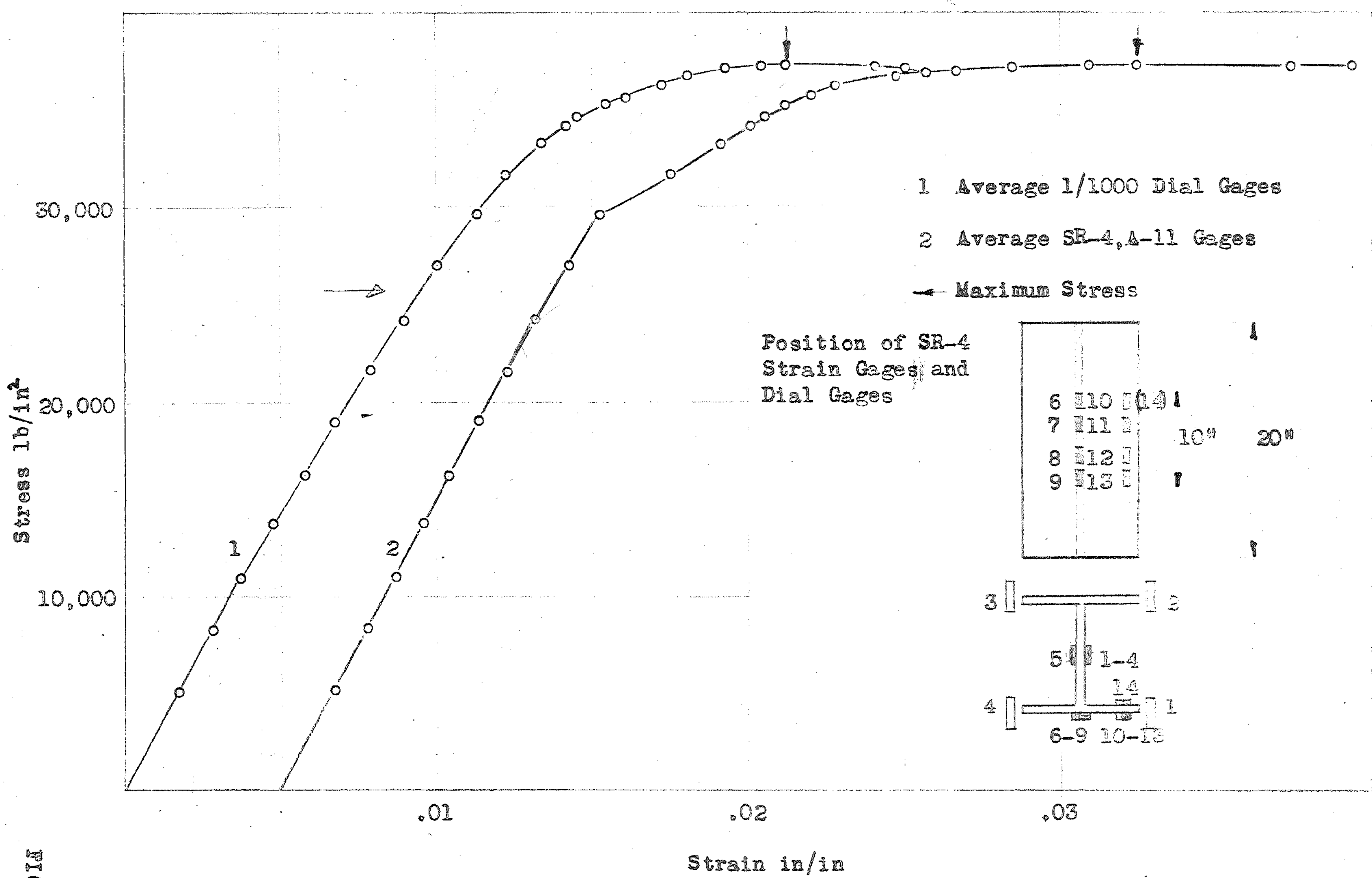
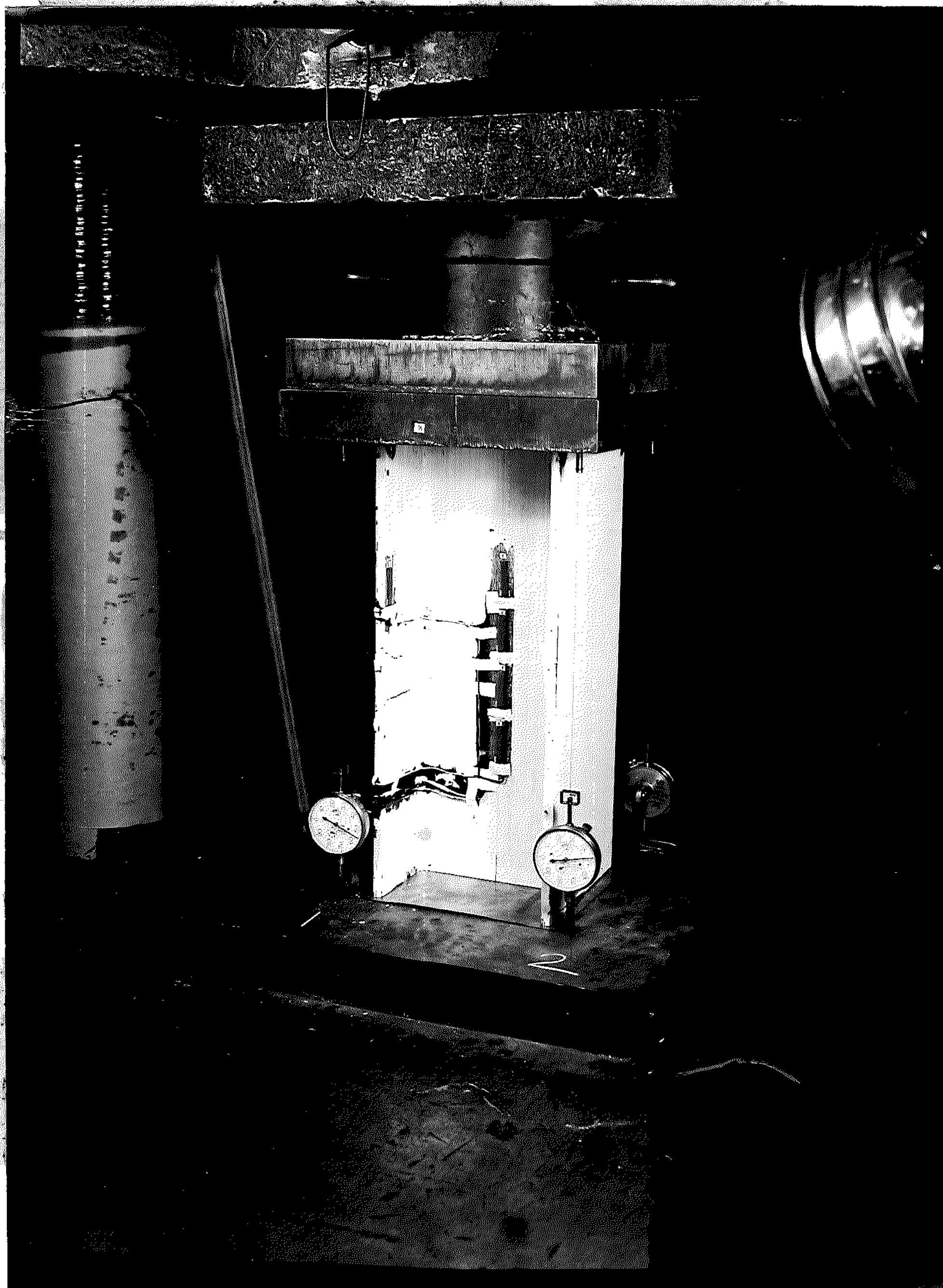
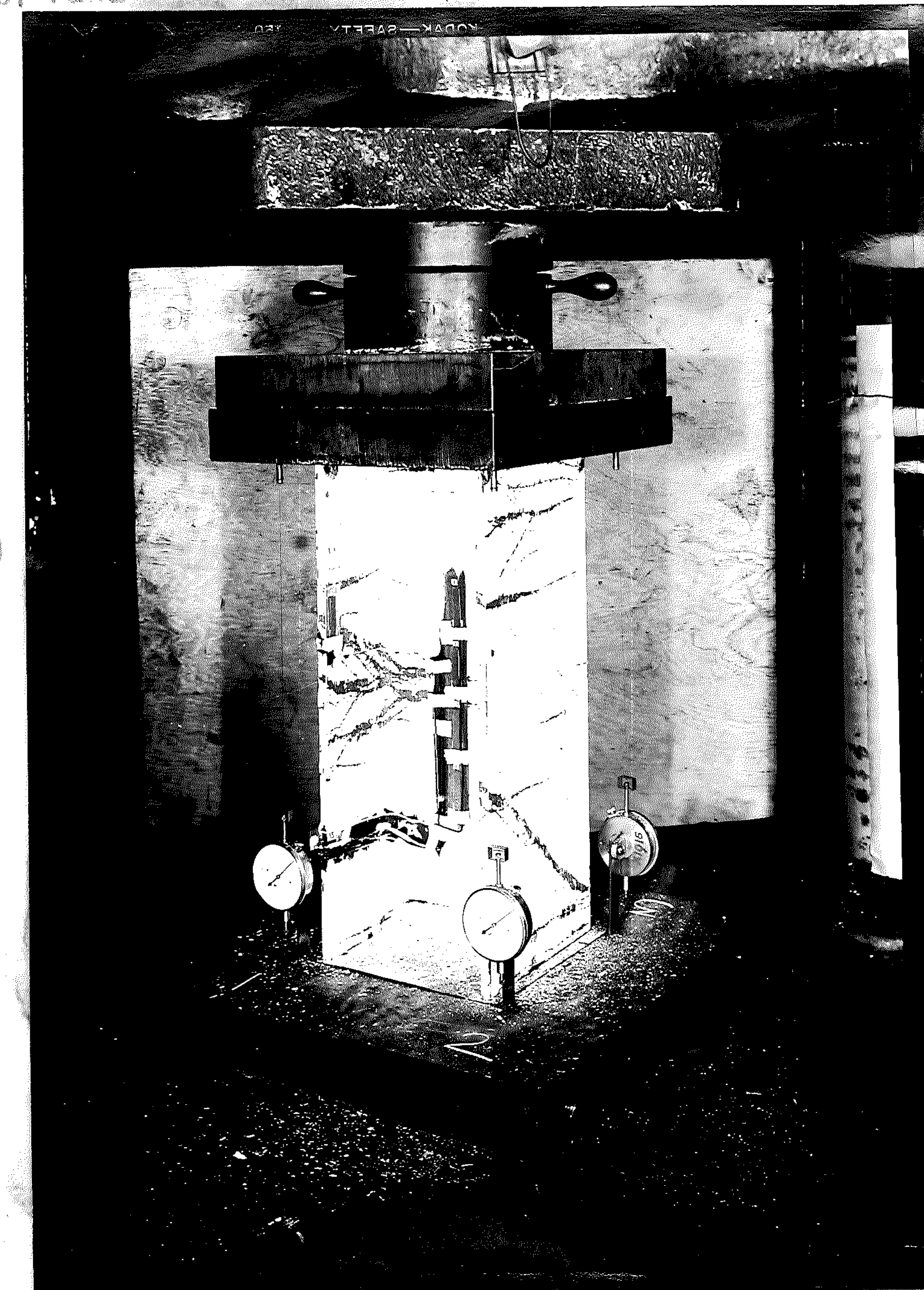


FIG. 11

(1) 39-15-24 (2) NEW GAGE END EFFECTS COPPER STRIPS BENDING OF PLATES (3) YIELD PROCESS



27 Kips



37 Kips

8

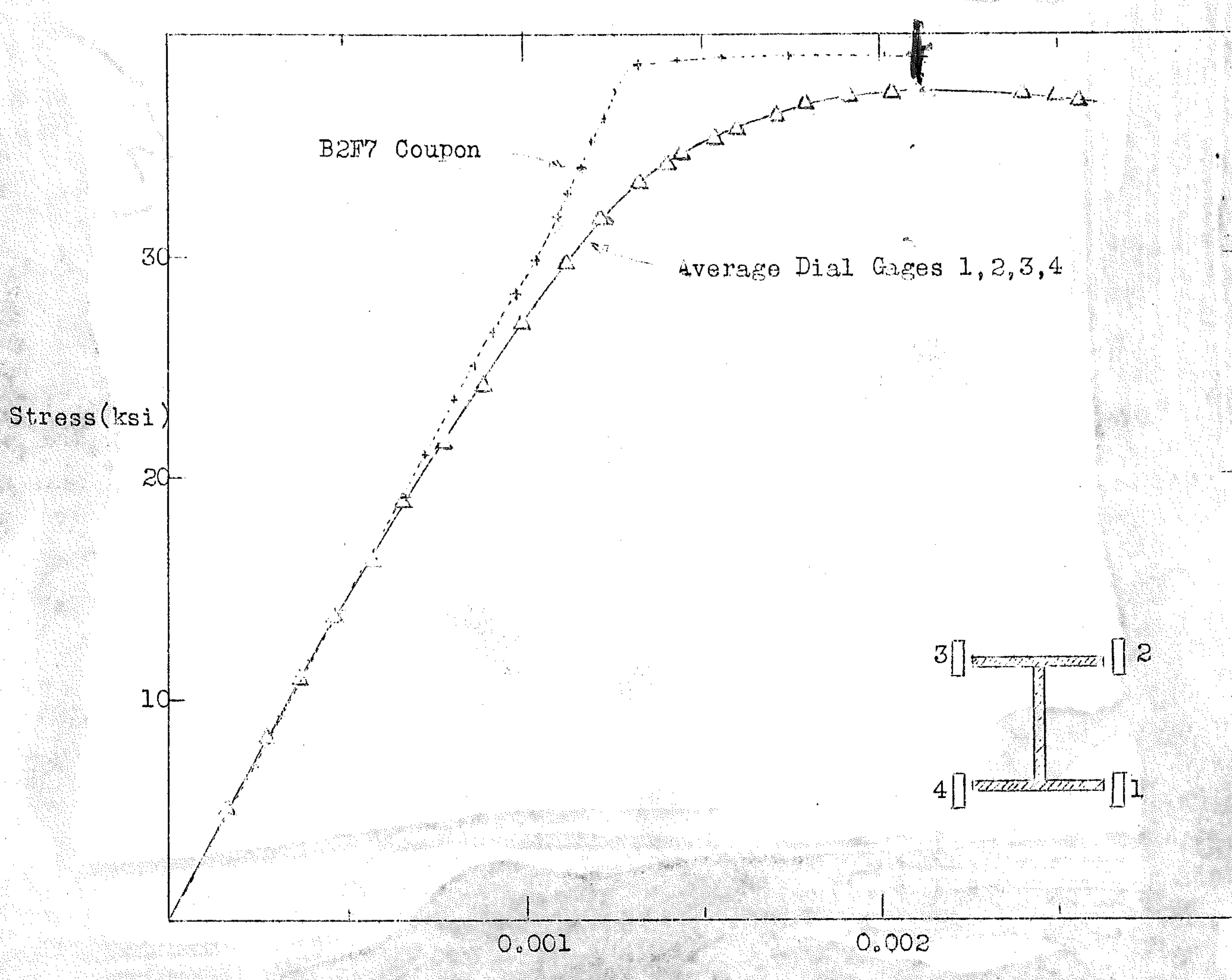

B2F7 Coupon
Average Dial Gages 1,2,3,4
Stress(ksi)
30
20
10
0.001
0.002
Strain (in/in)
3
2
4
1

Fig. a

220A.3 Encl. I

220A 9/17/51 (Residual Stresses) 18

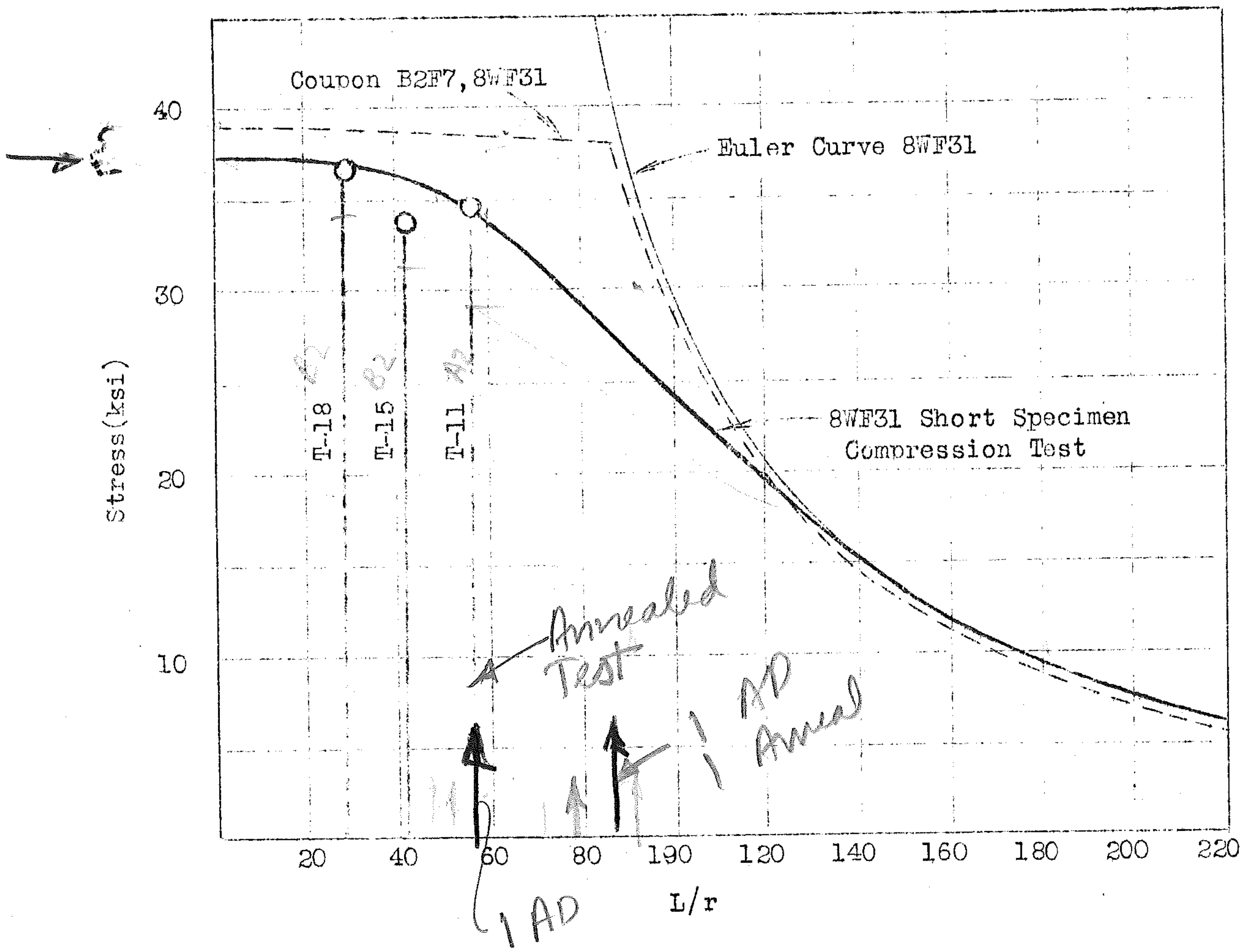
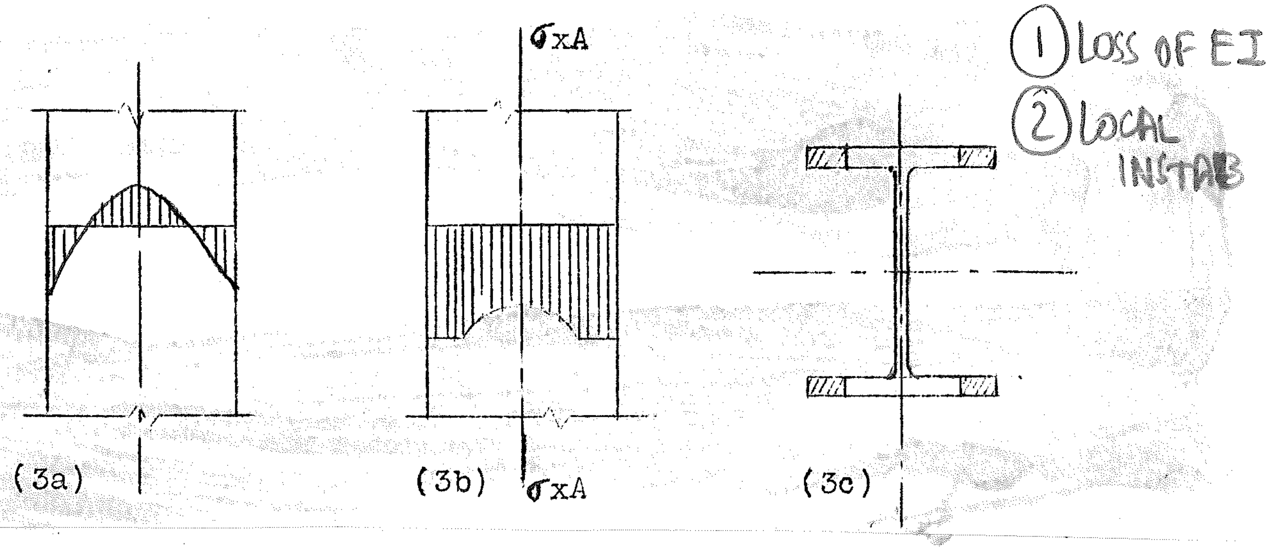
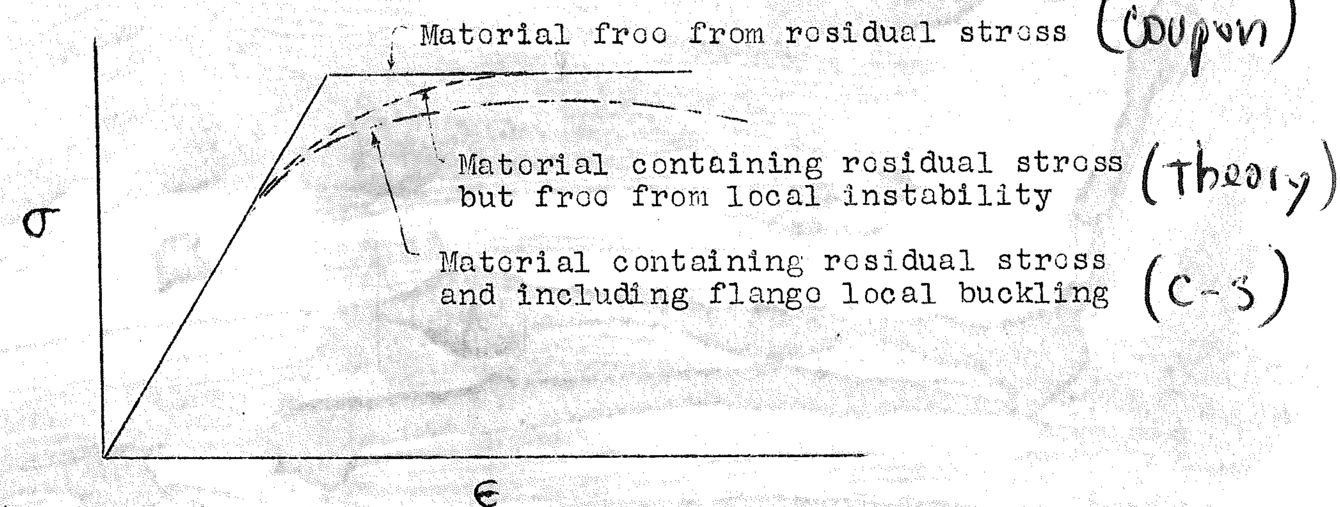


Fig. b

The strength of cols cannot be predicted on basis of TM → coupons



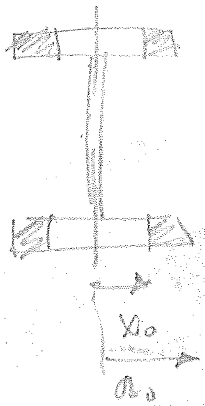
σxA
σxA
(3a)
(3b)
(3c)
① LOSS OF EI
② LOCAL INSTAB



Material free from residual stress (coupon)
Material containing residual stress but free from local instability (Theory)
Material containing residual stress and including flange local buckling (C-S)
σ
ϵ

Fig. 4.

For Flexure about Y-Y



$$k = \frac{x_0}{a_0}$$

$$I_{yy} = I_e \cong \frac{2t(2x_0)^3}{12}$$

$$x_0 = a_0 k$$

$$I_{yy} \cong A_F r^2$$

$$\frac{I_e}{I} = \frac{4}{3}\,\frac{t\,a_0^3 k^3}{A_F r^2}$$

$$\frac{E_t}{E} = \frac{A_e}{A} = \frac{A_w + k A_F}{A_w + A_F}$$

$$E_t A = (A_w + k A_F) E$$

$$\left(\frac{E_t A}{E} - A_w\right) = k A_F$$

$$k = \frac{E_t A}{E A_F} - \frac{A_w}{A_F}$$

$A_w ; A_F$

$$\boxed{I_{yy}\big|_e \cong \cancel{A_F}\, k^3 I_{yy}}$$

SHAPE FACTOR

YIELD PROCESS & LAT'L BUCKLING

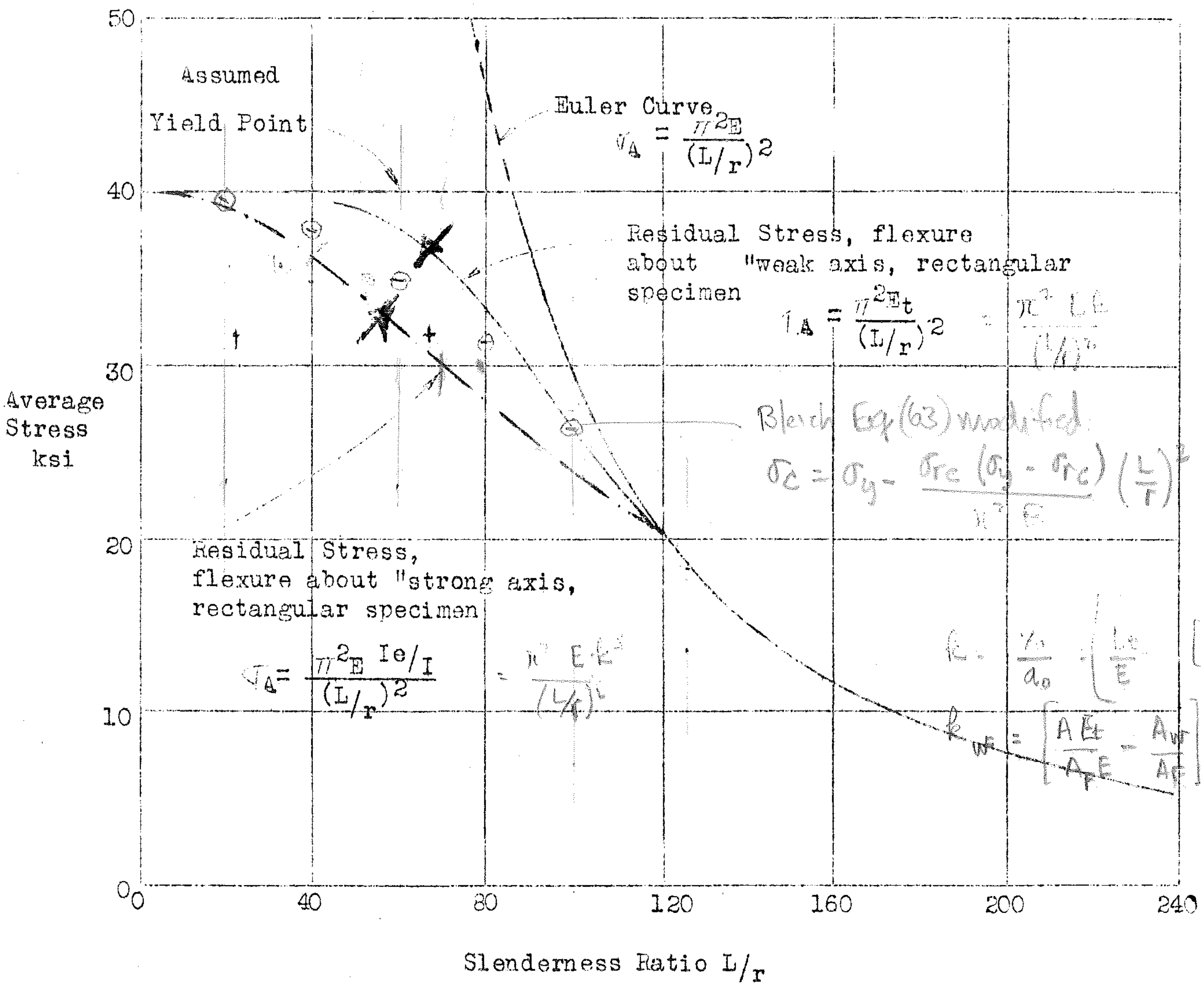


Figure 46 of the Report, "Residual Stress and the Yield Strength of Steel Beams"

Enclosure II

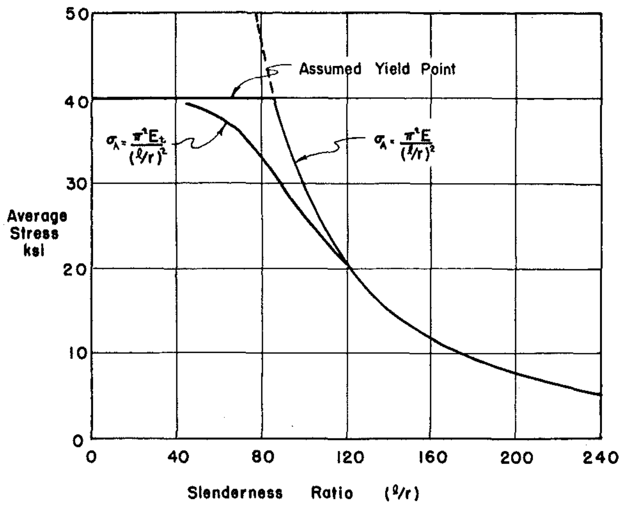


Fig. 46.- EFFECT OF RESIDUAL STRESS ON COLUMN CURVE

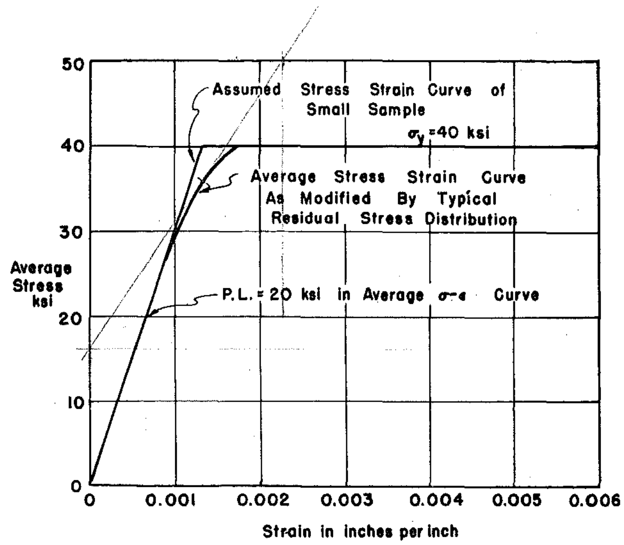


Fig. 47 - STRESS-STRAIN DIAGRAM FOR STEEL AS MODIFIED BY RESIDUAL STRESS

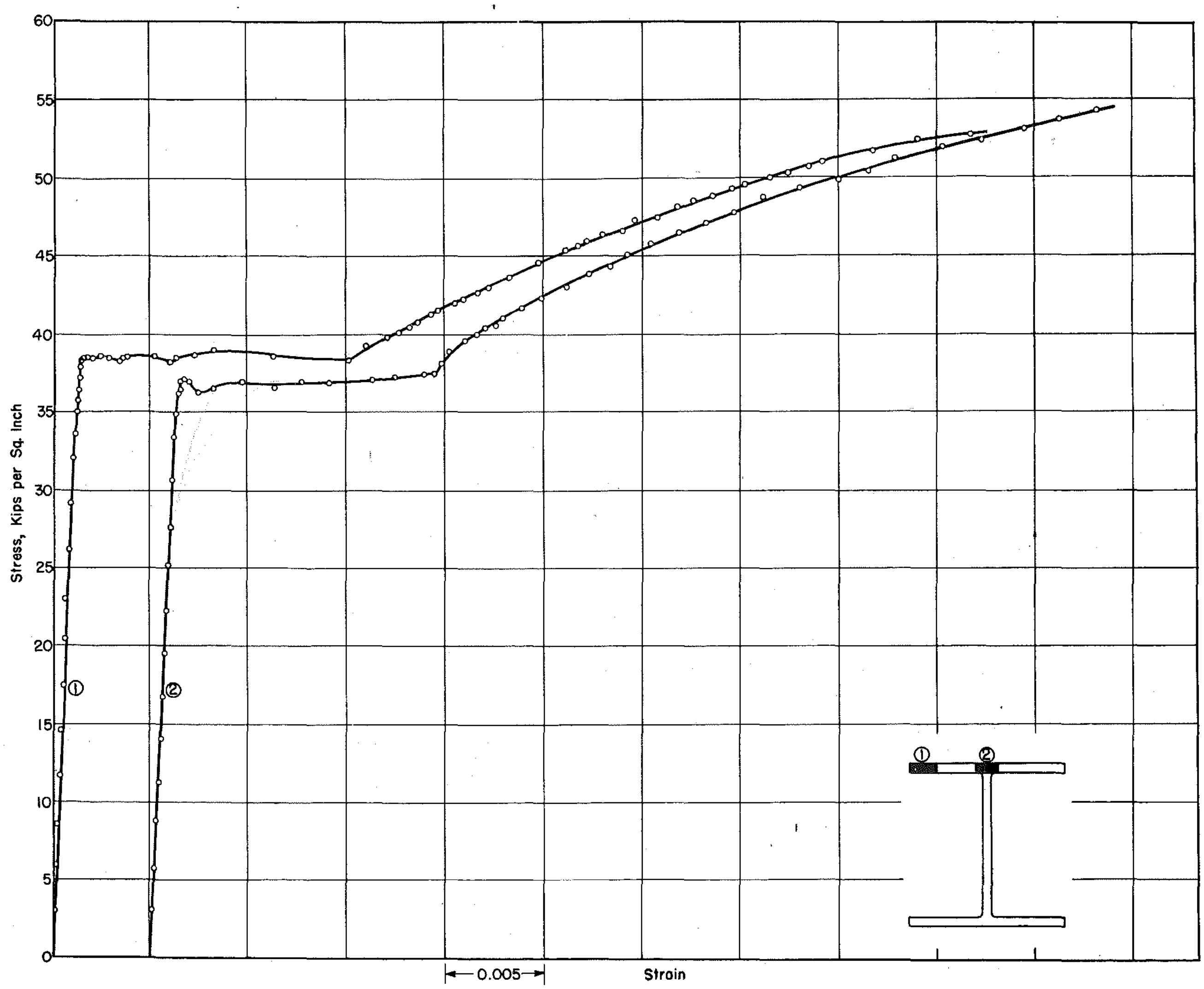


FIG. 48 - TENSION STRESS-STRAIN CURVES FOR AN 8WF40 BEAM
(Including strain-hardening range)

PILOT PROGRAM

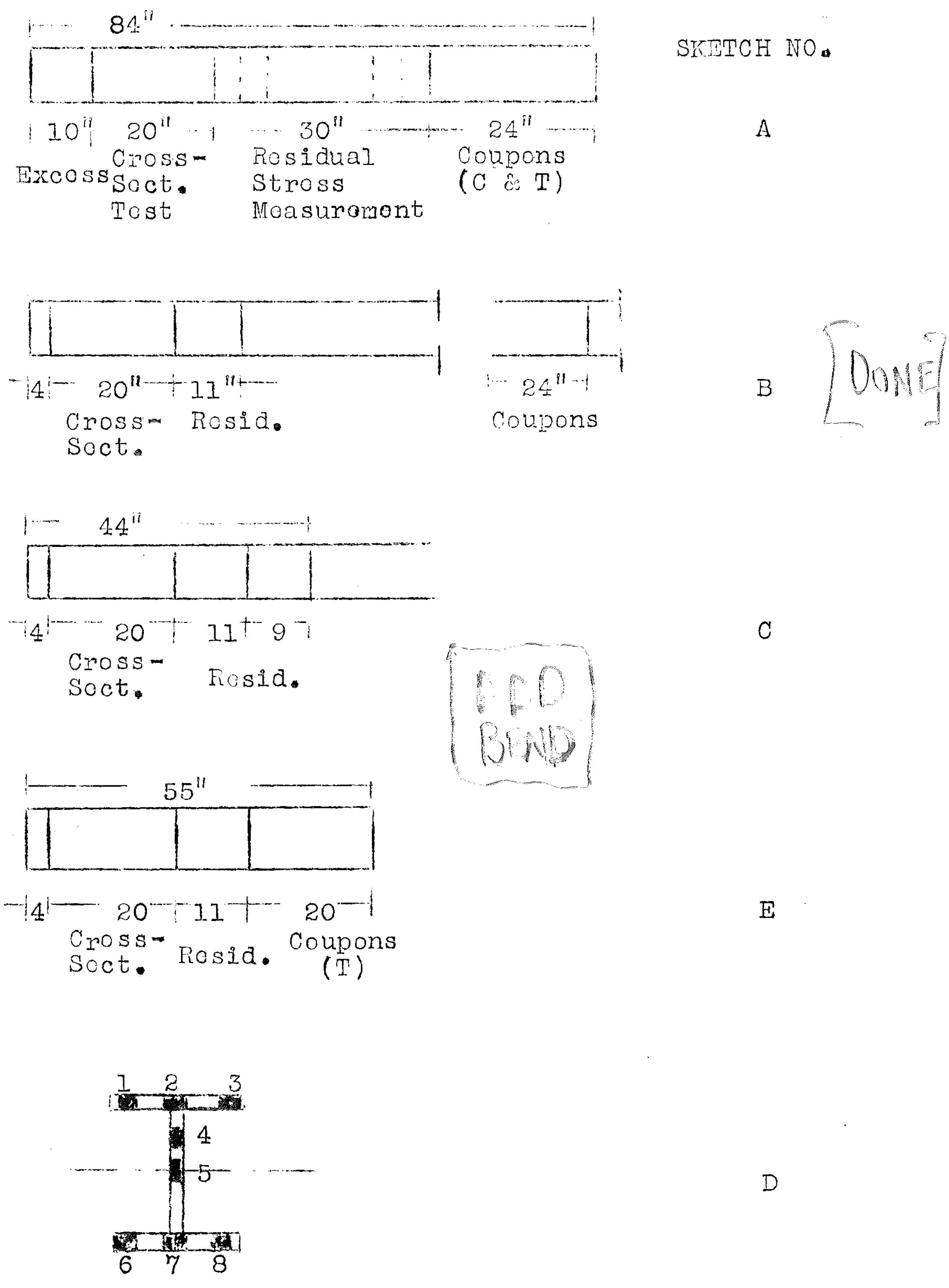
Table of Tests: 8WF31 Material

			4		3		2	1		
Heat No.	Ingot (Rolling)	Piece No.	Cross-Sect. As Del'd	Cross-Sect. ~~Normalize~~d Anneal	Coupon Ten.	Coupon Comp.	Residual Stress	Column Test As Del'd	Column Test ~~Normalize~~d Anneal	Sketch (Fig.1)
Tests completed and reported in Progress Report M										
I	B	2.2	T3	-	-	-	Yes	T15 T18	-	B & Fig.b
	B	2.1	-	-	Yes	Yes	-	-	-	D
	A	2	-	-	Yes	Yes	-	T11	-	-
Proposed tests										
I	B	2.3	-	-	-	-	YES	*a,b	-	Fig.b
	B	2.4	-	Yes	No	Yes	Yes	-	c**	E
	A	2	Yes	-	Yes	No	Yes	-	-	E
II	A	1.1	Yes	-	Yes	Yes	Yes	-	-	A
	A	2.4	Yes	-	No	No	Yes	-	-	C

---

* Pinned about the y-y ("weak") axis. L/r ≅ 56 and 85

** L/r = 85



Location of Coupons

Figure 1 - Cutting diagrams for test specimens.